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Sprayed concrete for final linings: ITA working group report

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Introduction

Thomas Franzen

The ITA Working Group on Shotcrete Use was established in Toronto 1989. As its first task, two state-of-the-art reports were published: 'Shotcrete in Tunnelling — Status Report 1991,' and 'Shotcrete for Ground Support: Guidelines and Recommendations — A Compilation.' They were also the basis for two articles in *Tunnelling and Underground Space Technology* Vol. 7, No. 4 in October 1992 and Vol. 8, No. 4 in October 1993. An enquiry on health and safety performed by Dr K. Ono from Japan, resulted in a report in 1995 and an article in *Tunnelling and Underground Space Technology* in Vol. 11, No. 4 in October 1996. After completion of these works, the main focus of the Working Group was on the durability of shotcrete since this has been a major issue in establishing this technology for the permanent lining of tunnels. Shotcrete has been accepted as a permanent lining in some countries, but not in general worldwide. To that end, the group has produced two documents about shotcrete used as a final lining. The first is a 'Guideline to the Processing of Durability Data', prepared by Mr K. Garshol, Norway. The second document was prepared by Mr N. Tomisawa, Japan, with the aim of demonstrating the use of 'Shotcrete as Permanent Lining' by compiling key data from nearly 150 cases in 11 countries. This compilation was done primarily as a general illustration of the practice used in several countries, but we have to point out that we cannot guarantee the relevance of every single figure in the table. Both documents are thus meant to contribute to a continued development and use of this technology, and we are glad to have them published also in *Tunnelling and Underground Space Technology*. Comments on the report may be sent to Mr Garshol (knutfg@aol.com) who is now the acting Animateur of the WG, or to Mr Tomisawa (tomisawa@konoike.co.jp).

Having been the Animateur of the Working Group for 10 years, I would like to express the sincere thanks of the Working Group and the International Tunnelling Association to those who have contributed generously over the years, and especially to Mr Garshol and Mr Tomisawa, who prepared the current documents. I also wish the group good luck in their continued efforts to enhance and promote a sound use of shotcrete in Tunnelling.

1. Sprayed concrete for final linings part 1: guideline to the processing of durability data

International Tunnelling Association Working Group No. 12, 'Shotcrete Use'
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1.1. Durability evaluation problems

The evaluation of durability of shotcrete linings in underground works turns out to be an extremely com-

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plex subject when trying to produce an overview and status description. There are a number of reasons for this situation and some of them are mentioned below.

The standard quality and property parameters checked for new shotcrete structures, mostly cover a time frame of 28 days with some covering up to 90 and 120 days. Relatively seldom are tests carried out, showing the effect of a time span of years. This compares poorly with the quite frequent project requirements of durability of 50–100 years, which is roughly 200–400 times longer.

When trying to draw conclusions on durability, this can only be made based on documented experience from a wide range of applications and regions — in other words, by systematic data collection and comparison. This creates the other main obstacle: how can it be possible to compare shotcrete durability among specific shotcrete applications (these are referred to as 'objects' in this report since several different types of application and site conditions may be present within a single tunnel or project) and identify reasons for observed behaviour, when almost all factors vary from case to case? This variation exists within all the main durability aspects:

1. Exposure of the sprayed concrete, in the widest sense, to different types of quality and strength reducing processes. Examples include:

- temperature variation, humidity variation, freeze/thaw cycles;
- loads and imposed deformation, vibration, impacts and abrasive action; and
- chemical attack from ground water and other liquids; aggressive components in the atmosphere.

2. The shotcrete exposure resistance capacity, in relation to the exposure processes.

- Mechanical strength in relation to different types of imposed loads.
- Ductility and crack distribution ability for the reduction of crack width.
- Resistance against sulfates, chlorides, carbonation, alkali/aggregate reaction, etc.
- Resistance to freeze/thaw, wetting/drying, dynamic loads.

3. Exposure time duration

- This may appear as, simply, the age of the shotcrete, but the duration of exposure to different processes may vary widely between given shotcrete object locations. The structure may be part of the time water filled and part of the time dry, conditions may change due to change of use of the structure, etc.

The second point above (shotcrete resistance) covers the shotcrete product itself and entails probably the biggest variation problem in relation to the possibility of reasonable comparisons. Shotcrete has been used extensively for underground structures for more than 30 years and during this time there has been a dramatic development of the process. We have dry mix and wet mix spraying methods, hand-held and remotely-controlled mechanised application, new cement types, fly ash, micro-silica, steel fibres, a range of concrete admixtures, a number of curing methods and an enormous development within shotcrete accelerators. Also, the equipment quality has improved, including important issues like accelerator dosage accuracy and nozzle design.

Another extremely important issue in shotcrete production can be covered by the expression 'execution' which again adds to the complex set of factors influencing the second point mentioned above. It is generally known and accepted that project factors, such as the skill of the nozzle operator, the quality of the equipment, the substrate preparation work, the way of fixing the reinforcement, working light levels, ventilation conditions, ground water conditions at time of spraying, etc., can each substantially influence the final product (even when all other factors are constant).

One further main aspect of durability can be brought into the picture, adding complexity to the task of comparing objects, communicating experience and making objective conclusions:

4. Balance between requirements and design.

- Shotcrete durability can be very poor, even if all aspects of the execution are flawless and all the materials are as specified. This occurs if the durability requirements of the structure are out of balance with the specified quality and durability parameters used as a basis for shotcrete production. Nobody will experience any durability problem with low-grade shotcrete when used for a temporary, non-structural application. The same specified shotcrete could fail miserably, if the expectations were for 50 or 100 years of service life.
- Furthermore, a high grade, perfectly executed shotcrete, subjected to widespread cracking caused by wrong dimensioning (design), could easily suffer durability problems by reinforcement corrosion linked to cracks, concrete cover spalling and a too early repair demand. In such a case, there would be no real link to the exposure situation, poor shotcrete resistance or the exposure duration.
- A person who knows the quality and durability of a Volkswagen Beetle and buys one, will be reasonably satisfied. The person who requires the qualities of a Rolls Royce limousine and still specifies and buys a Beetle, will become very disappointed.

1.2. Status of existing linings

The ITA Working Group on Shotcrete has received national contributions giving specific information on the status of different types of shotcrete objects (see Part 2 of this report). Since all this information has been presented without a common methodology, the normal problem of comparison and of stating generally applicable conclusions is present. Some of the objects are tunnel linings; some are repair works on concrete substrate, etc. The application methods are both dry and wet and reinforcement has been reported as both mesh and as steel fibres.

As could be expected, the results reported cover the full variation from excellent condition after decades of service life (which seems to be a major part of the reported objects), to serious damage after a relatively short time. When damage has occurred, in most cases, there are quite evident reasons (mostly limited to local features), such as water and frost, chemical attack and situations causing extensive cracking and bond failure. The primary reasons for the success stories are not as clear and obvious.

Actually, a state-of-the-art report based on the collected data provided in Part 2 and summing up the experience and technical execution level in different geographical areas seems to be a bit premature. The common basis, or methodology for processing of technical information in a format that will allow the compilation of such a report, is presently missing. This state of affairs and the above general description of the problem complexity are the motivation factors and background for preparing and presenting this data compilation matrix.

1.3. Recommendations

The durability of shotcrete structures is a relative term, depending on issues such as the present age of the structure, compared to the specified service life expectancy and the actual exposure processes involved.

To be able to compile experience data in a systematic and meaningful way and to allow specification of shotcrete to meet a targeted lifetime, the durability subject has to be broken down into its individual components. This will include establishing what measured quality parameters are important for the shotcrete resistance against which exposure processes. By creating such a matrix for data input and processing of shotcrete experience, it appears possible to reach reasonably objective conclusions on how to produce durable shotcrete structures.

When working on durability issues, such a matrix could be used for structuring empirical data and for the evaluation of a given existing or future project. For maximum benefit of such information, in terms of usefulness and accuracy, it is important that as much as possible is known about all the four main durability aspects:

1. complete information about the object exposure situation;
2. all necessary shotcrete material information, to be able to quantify exposure resistance parameters;
3. duration of exposures, if necessary, split on the local set of processes; and
4. design basis and life time expectancy compared to specifications and work execution.

1.4. Description of proposed shotcrete durability data matrix

The matrix is shown in three separate forms (Tables 1–3) and is meant to be applicable to existing structures, as well as for future execution of shotcrete applications. Supplementary information (not fitting the forms) should be added as attachments identified in the proper positions of the matrix forms.

1.4.1. Table 1

Table 1 gives the object identification details, design service life (if any) and age of the structure (if existing) at the time of data input. Furthermore, the exposure situation must be established as accurately as possible. The different types of exposure are self-explanatory and cover environmental, mechanical load, and other exposure types. The exposure duration in percentage of age (of the structure) is there to allow a distinction between exposure factors, if necessary. It may happen that, for instance, a diversion tunnel is water-filled only some of the time.

1.4.2. Table 2

Table 2 is also quite self-explanatory and can be used for already executed spraying, or for input of the planned shotcrete application. Revision of data, if changes occur, should be carried out as required. This table gives information about execution, including mix design details, method of application, curing of the concrete, etc. Again, the table should be seen as a checklist to make sure that the main issues are covered, but not as a limitation.

1.4.3. Table 3

Table 3 contains the evaluation matrix. It must be clearly stated that the way to use this table will have to be decided by the user. The ITA Working Group cannot dictate the approach to durability evaluations in different countries and within different projects. Therefore, the matrix can and should be used in a flexible way. In the first column, a list of shotcrete quality parameters is given, all of them of importance to durability. The next column can be used to assign an importance priority to given parameters. Obviously, the freeze/thaw resistance has a higher priority for a slope protection project in Scandinavia, than the salt attack resistance, which would be more applicable in a sub-sea tunnel. The priority must clearly be established case by case, based on the particular situation of each project.

Column 3 will show parameter values as specified for the structure by the designers. Column 4 shall identify the actual values as built, and as measured by control of the structure. In the case of older structures, some of the 'actual' figures may suffer degradation caused by exposure factors. By calculating the actual/required factor '*R*,' a crude expression for remaining exposure resistance is derived. Column 6 can then be used for a rating of the *R*-factor, based on the object specific situation and the level of safety margin decided by the responsible body. For example, if the carbonation depth is 15 mm after 3 years, the concrete cover over the reinforcement is 30 mm, and cover spalling will be a serious problem, then the classification should be 'warning' or 'poor,' or, if there is no reinforcement, the carbonation depth is of marginal or no importance.

Column 7 should be used to specify the test methods used to check the different parameters. The Shotcrete Working Group has deliberately chosen not to mention particular methods or standards, because the preferences will vary by country and with a number of other aspects.

Column 8 is very important. It is normally not possible to make reasonable assumptions or statements about durability, without knowing what policy applies regarding inspection and maintenance. Guaranteeing a service life of 100 years without inspection and maintenance will be totally different than if it is a part of the

Table 1
Data Record for Project Identification, Location, Age and Exposure Conditions

PROJECT NAME:		
Type of Project:		
Project location:		
Owner and Contractor:		
Object (part of tunnel):		
Geology at object:		
Shotcrete object planned design life, years:		
SHOTCRETE OBJECT EXPOSURE SITUATION	Object age	Exposure duration, % of age
a) Environmental exposure:		
Temperature minimum, C:		
Temperature maximum, C:		
Temperature typical, C:		
Relative humidity minimum, %:		
Relative humidity maximum %:		
Relative humidity typical %:		
Freeze/thaw cycles per year:		
In ground water contact (Yes/No):		
Ground water contact description:		
Most aggressive GW component:		
Concentration of this component:		
Atmosphere contact (Yes/No):		
Most aggressive gas in local atmosphere:		
Concentration of this gas:		
b) Mechanical load exposure:		
Expected maximum crack width, mm:		
Load capacity utilization, %		
Vibration load of relevance, describe:		
Impact load of relevance, describe:		
Abrasion load of relevance, describe:		
c) Other exposures, any type:		
Aggressive liquid other than in GW:		
Aggressive gas other than in the atmosphere:		
Other durability reduction factors		
Describe:		
d) Cracking or other signs of damage:		
Spacing and length of cracks		
Typical and maximum crack width		
Other damages, describe		
Information input date:		Sign.:

design that inspection will be carried out every 15 years (and local repairs will be carried out as necessary). This difference also applies to the minimum requirements for the mix design, quality assurance (QA) system, and quality of execution of new structures. Requiring a durability of more than 100 years without inspection is not really to be recommended and will involve uncertainty, even if investing substantial resources during execution.

Column 9, with the overall durability rating, is the project specific conclusion at the date of the data input. This evaluation should not be parameter specific, but rather an overall status definition for the whole structure, based on the parameter priority and established exposure resistance.

The matrix has been developed based on a primary draft from Japan with later input from several countries. The document should be considered a living document and should be revised when and if proposals for improvement are received.

2. Sprayed concrete for final linings part 2: compilation of permanent shotcrete linings

International Tunnelling Association Working Group No. 12, 'Shotcrete Use'
N. Tomisawa, Japan

The compilation presented in Table 4 is based on an enquiry to members of the working group. The data is to be seen as a general illustration of the practice used in several countries. It cannot be used as a reference for details in different projects as we cannot guarantee the relevance of every single figure in the table.

Table 2
Data Record for Shotcrete Method and Mix Design

	SHOTCRETE METHOD AND MIX DESIGN	
a)	**Practical Information:**	
	Method of application, wet or dry	
	Type of reinforcement, mesh or fibres	
	Equipment package, describe:	
	Hand held, or hydraulic manipulator	
	Excavation method, describe	
	Tunnel cross section, m^2	
	Typical average thickness sprayed	
	Typical number of layers sprayed	
	Typical equipment output, m^3/h	
b)	**Shotcrete mix design per m^3:**	
	Type of aggregate and sand	
	Sand modulus of fineness	
	Aggregate coeff.of water absorption	
	Type of cement, kg/m^3	
	Micro silica or fly ash, type, kg/m^3	
	Other activities (fillers or other), kg/m^3	
	Steel fibres, type, dimension, kg/m^3	
	Sand fractions, broken or natural, kg/m^3 for each	
	Admixtures with type, name and kg/m^3	
	Accelerator or other materials added in the nozzle, type, kg/m^3	
	Hydration control admixture kg/m^3	
	Open time of batched concrete	
	Water/cement ratio	
	Consistency after batching, Slump	
	Consistency during spraying, Slump	
c)	**Method of curing:**	
	Curing executed, Yes/No	
	Spray-on membrane, type, kg/m^2	
	Curing by admixture, type, kg/m^3	
	Water curing, describe how, duration	
d)	**Attach available materials test certificates, sieve lines, chemical content, etc.**	

Table 3
Data record for shotcrete quality and durability measurements

Shotcrete quality parameter	Durability priority of parameter	Required parameter value	Actual parameter value	Exposure resistance R = actual/required	Classification A: Durable B: Warning C: Poor	Test method applied	Time between inspections (and repair) years	Overall durability rating
Compressive strength								
Bond strength to substrate								
Bond strength inter-layer								
Flexural strength								
Energy absorption (ductility)								
Elastic modulus								
Shotcrete density								
Permeability								
Freeze/thaw resistance								
Scaling resistance								
Chemical attack resistance								
Carbonation depth								
Salt attack resistance								
Alkali-aggregate reaction								
Boiled absorption								
Volume of voids								

Table 4
Compilation of permanent shotcrete linings

No.	Country	Name	Tunnel	Time	Length (m)	Finished cross section			Shotcrete		Remark	Reinforcement
						Width (m)	Height (m)	Area (m^2)	Thickness (cm)	Compressive strength (MPa)		
1	Austria	Water power plant Kaunertal/Tyrol	Surge tank machine chamber	1962	–	–	–	–	–	55 (year 1982)	Single shell concrete lining, sulfate resistant cement	–
2	Austria	Hallstadt/Upper Austria	Road	1966	1063 1203	5.4	5	24	15	69 (year 1996) 29 (year 1964)	Single shell – corrosion of reinforcement according to water inflow	–
3	Austria	Brandberg/Tyrol	Road	1976	2130	7	–	–	10	30 (year 1997)	Single shell — rough, surface, less water dripping from the roof	–
4	Austria	Gstalda/Tyrol	Road	1980	480	–	–	–	Variable as Necessary	37 (year 1997)	Single shell — water inflow at weak section	–
5	Austria	Safety gallery for Plabutasch tunnel	Road	–	–	–	–	–	–	36 (year 1997)	–	–
6	Belgium	Tunnel de Lustin	Twin trsck rail	1994							Life duration:120 years	p/fibre
7	Canada	Stave Falls British Columbia	Hydro electric	1997/98	200	6.6	6.6		10	40 (28days)	2-pressure headache tunnels	Steel fibre 55kg/m^3
8	Canada	BC Rail Tumbler ridge British Columbia	Railway	1982/83	640	5.5	8.5		10	40 (28days)	New rail tunnels	Steel fibre 60kg/m^3
9	Canada	BC Rail Howe Sound British Columbia	Railway	1988	700	5.5	8.5		10	40 (28days)	Rehabilitation of three old rail tunnels	Steel fibre 60kg/m^3
10	Canada	C.P. Rail Rogers pass British Columbia	Railway	1986/87	1000	5.5	8.5		10	40 (28days)	New Shaughnessy tunnel	Steel fibre 60kg/m^3
11	Czech	Dlouhé stráné	Power station	1985	250		45	*(11 250)	55	20	*(Cavern walls)	4 × steel mesh
12	Czech	Dlouhé stráné	Power plant	1985	110	16	12	130	45	20	Transformer cavern	3 × steel mesh
13	Czech	Pec pod snézkou	Sewage plant	1987	60	18	16	160	45	20	Arch	3 × steel mesh
14	Czech	Bohuslavice	Road	1995	68	9	6.5	59	40	20		3 × steel mesh, lattice girders
15	Czech	Prachovice	Gallery for factory	1996	920	4	3	10	30	20		2 × steel mesh rolled steel profile
16	Czech	Jaroméí	Public sewer	1996	850	3.5	2.4	6	20	20		2 × steel mesh rolled steel profile
17	Czech	Dlouhé stráné	Cabel adits	1996	720	4	3.5	12	10	20		1 × steel mesh anchors

No.	Country	Name	Tunnel	Time	Length (m)	Finished cross section			Shotcrete		Remark	Reinforcement
						Width (m)	Height (m)	Area (m^2)	Thickness (cm)	Compressive strength (MPa)		
18	Czech	Ceská skalice	Public sewer	1996	120	3.5	2.4	6	20	20		2 × steel mesh rolled steel profile
19	Czech	Blansko	Railway	1997	434	6.8	6.4	43	15–30	20	Repair	3 × steel mesh, lattice girders
20	Czech	Praha	Subway	1997	141	5.2	4.5	19	25–30	20	Short section without formwork	2 × steel mesh, lattice girders
21	Czech	Brno	Electrical network	1997	7800	5.2	4.5	18–21	35	> 20	Primary duct	2 × steel mesh
22	Czech	Praha	Eletrical network	1997	4600	2.5	3.9	8	45	20	Secondary duct	3 × steel mesh
23	Czech	Brno	Electrical network	1997	2400	2.5	3.8	8–11	30	20	Secondary duct	2 × steel mesh
24	Czech	Loket	Sewage plant	1997	156	9; 5.2; 3.8	8	30; 18; 11	35	20	Arch	3 × steel mesh
25	Czech	Hradec králové	Public sewer	1997	680	3	2	5	20	20		1 × steel mesh anchors
26	Czech	Les království	Injection gallery for water dam	1997	50	3	2.5	6	30	20		3 × steel mesh rolled steel profile
27	Czech	Meziméstí	Gallery for draining water	1997	80	4	2	8	20	20		2 × steel mesh anchors
28	Czech	Praha	Subway	1998	140	9.1–11.0	5.6–6.9	41–61	45	> 20	Changes of cross section Prague's metro-double track tunnel	2 × steel mesh, lattice girders
29	Czech	Praha	Gallery connecting new transformers	1998	737	2.65	2.8	7	20	20		2 × steel mesh rolled steel profile
30	Czech	Praha	Electrical network	1998	4800	3	3.4	8	45	> 20	Primary duct	3 × steel mesh
31	Czech	Príbram	Plug of gas cavern	1998	4 × 10	6.4	4.5	22	1000	> 40		Steel fibre
32	Czech	Liberec	Public sewer	1998	940	3	2.5	6	20	> 20		2 × steel mesh anchors
33	Germany	Gelsenkirchen	Subway	1982					10 + 15		Steel mesh	Steel fibre
34	Germany	Bielefeld	Subway	1988	104	5.55	6.01		10 + 15		Lattice arch	Steel fibre
35	Japan	Seikan	Service	1985	22 286 17 789	1.8	4.25	–	15–20	F'ck = 18		
36	Japan	Aninose	Road	1992	237.0	6	5.5	–	5	F'ck = 18		

No.	Country	Name	Tunnel	Time	Length (m)	Finished cross section			Shotcrete		Remark	Reinforcement
						Width (m)	Height (m)	Area (m^2)	Thickness (cm)	Compressive strength (MPa)		
37	Japan	Arima	Railway	1995	114.0	4.6	5.6	–	5 + 15 + 10 + 20		To shorten a term of construction	Vinylon fibre
38	Japan	Egeyama	Railway	1995	251.0	6.75	6.5	–	5 + 15 + 10		To shorten a term of construction	Steel fibre
39	Japan	Karisaka	Ventilation	1995	1586.0	8.5	5.55	–	10 + 10	57.1	Because of difficulty in setting forms	–
40	Japan	Shinitukigawa	Penstock	1996	4651.0	$D = 4.3$		–	36 032	26 (7days)	To expand a tunnel section	–
41	Japan	Maiko	Ventilation	1996	420.4	9.5	8.55	–	15 + 5	32.8 31.3	To reduce cost Because of difficulty in setting forms	Vinylon fibre
42	Japan	Takayama-dome	Art museum	1997		$R = 20$	$H = 20$	–	16 + 8	F'ck = 21		Steel fibre
43	Norway	Vardø	Road (subsea)	1982	2890	8	6	45 (T8)	0–10	C25	Rock support	None
44	Norway	Kvalsund	Road (subsea)	1988	1650	8	6	45 (T8)	0.5–8	C45	Rock support	75 kg Dramix 30/50
45	Norway	Maursund	Road (subsea)	1991	2122	8	6	45 (T8)	1–8.5	C45MA	Rock support	50 kg steelfibre
46	Norway	Nappstraumen	Road (subsea)	1990	1780	8	6	45 (T8)	1–10	C45MA	Rock support	75 kg steelfibre
47	Norway	Freifjord	Road (subsea)	1992	5086	11	7	65 (T11)	6.5–14	C45MA	Rock support	75 kg and 50 kg.
48	Norway	Fannefjord	Road (subsea)	1991	2743	11	7	65 (T11)	2–10	C45MA	Rock support	50 kg Dramix(30)
49	Norway	Valderøy	Road (subsea)	1987	4222	11	7	65 (T11)	2–13	C35	Rock support	
50	Norway	Ellingsøy	Road (subsea)	1987	3520	11	7	65 (T11)	0–8.5	C35	Rock support	75 kg EE-fibre
51	Norway	Godøy	Road (subsea)	1989	3835	8	6	45 (T8)	3.5–18	C45	Rock support	75 kg EE-fibre
52	Norway	Byfjord	Road (subsea)	1992	5875	11	7	65 (T11)	2–17.5	C45MA	Rock support	55 kg, EE(25)
53	Norway	Mastrafjord	Road (subsea)	1992	4424	11	7	65 (T11)	1.5–17	C45MA	Rock support	55 kg EE(25)
54	Norway	Flekkerøy	Road (subsea)	1989	2327	8	6	45 (T8)	4–19	C45MA	Rock support	75 kg
55	Norway	Hvaler	Road (subsea)	1989	3751	8	6	45 (T8)	1–14.5	C45	Rock support	60 kg, Dramix (30)
56	Norway	Skarvberg	Road	1970	2920	–	–	45	0–6	C35	Dry method	
57	Norway	Løvstakk	Road	1968	2045	–	–	45	–		Sprayed portals, dry method	

No.	Country	Name	Tunnel	Time	Length (m)	Finished cross section			Shotcrete		Remark	Reinforcement
						Width (m)	Height (m)	Area (m^2)	Thickness (cm)	Compressive strength (MPa)		
58	Norway	Ringnes	Road	1986	335	–	–	55	10		Sprayed portal	
59	Norway	Sortvik	Road	1990	500	8	6	45 T(8)	0–7	C35		75 kg EE
60	Norway	Pollfjell	Road	1983	3230	–	–	45	5–7	C45	Sprayed in 1991	50 kg
61	Norway	Riven	Road	1983	–	–	–	–	–	C45	Sprayed in 1992	
62	Norway	Være	Road	1989	1625	–	–	50	3–12	C35		75 kg EE (18)
63	Norway	Grillstadhaugen	Road	1989	750	–	–	50	3–6	C35		75 kg Dramix 30/50
64	Norway	Stavsjøfjellet	Road	1990	1720	–	–	50	3–10	C35		75 kg Dramix 30/50
65	Norway	Runehammaren	Road (closed)	1963	–	–	–	40	1–3	–	Dry method, rock stresses	
66	Norway	Haga	Road	1971	690	–	–	45	0–5	–	Rock stresses	
67	Norway	Eikefet	Road	1979	4910	–	–	45	0–5	–		
68	Norway	Mundalsberget	Road	1974	1085	–	–	45	0–5	–		
69	Norway	Løvstakk	Road	1968	2045	–	–	45	0–4	–	Dry method	
70	Norway	Lauåsen	Road	1985	232	–	–	45	3–6	–		–
71	Norway	Gya	Road	1989	500	–	–	45	3–6	–		–
72	Norway	Røyrdalen	Road	1979	722	–	–	45	0–5	–		
73	Norway	Lovraeidet I	Road	1956	207	–	–	45	0–3	–	Dry method	
74	Norway	Velaskaret	Road	1964	294	–	–	45	0–4	–	Dry method	
75	Norway	Varstad	Road	1982	200	–	–	45	0–4	–		
76	Norway	Lavoll	Road	1970	373	–	–	45	0–4	–	Dry method	
77	Norway	Kleven	Road	1960	206	–	–	45	0–2	–	Dry method	
78	Norway	Åtland	Road	1970	360	–	–	45	0–3	–		
79	Norway	Strandveien	Road	1992	–	–	–	–	6	C40	Net reinforcing sprayed concrete	
80	Norway	Gudvanga	Road	1987	11 428	–	–	45	0–7	–	Rock stresses	Steel fibre
81	Norway	Stonndal	Road	1971	2240							
82	Norway	Berdal	Road	1971	4270	–	–	45	0–6	–	Net reinforced sprayed concrete, rock stresses	
83	Norway	Bergaskred	Road	–	480							

No.	Country	Name	Tunnel	Time	Length (m)	Finished cross section			Shotcrete		Remark	Reinforcement
						Width (m)	Height (m)	Area (m^2)	Thickness (cm)	Compressive strength (MPa)		
84	Norway	Seimsdal	Road	1960	1515	–	–	45	–	–	Sprayed concrete applied at a later stage	Steel fibre
85	Norway	Merkjeskred	Road	1983	1530	–	–	45	0–6	–	Rock stresses	Steel fibre
86	Norway	Fodnes	Road	6600	1994	–	–	45	0–10	C40	Rock stresses	Steel fibre
87	Norway	Lærdal	Road	24 500	2001 (open for traffic)	8.5	6.2	48	6–15	C40	Rock stresses	Steel fibre
88	Norway	Innfjord	Road	6594	1991	–	–	45	0–10	–	Rock stresses	Steel fibre
89	Norway	Vike	Road	3520	1989	–	–	40	0–6	–	Rock stresses	Steel fibre
90	Norway	Heggura	Road	5280	1982	–	–	40–45	0–5	C35	The first tunnel using wet mix steel fibre reinforced sprayed concrete. Rock stresses.	Steel fibre
91	Norway	Kobbskaret	Road	4457	1986	–	–	45	0–15	–	Rock stresses	Steel fibre
92	Norway	Stetind	Road	2759	1990	–	–	45	0–10	–	Rock stresses	Steel fibre
93	Norway	Lieråsen	Rail	10 700	1973	–	–	70	2–25	35–45	Rock stresses	
94	Switzerland	Nations — Joli, City Geneva	Cable & Infrastructure Gallery	1972	2579	∅ 3.0		7.1	10		New tunnel dry shotcrete, mats + anchors, smoothed surface	
95	Switzerland	Buchberg (Schmerikon)	Highway, two tubes	1973	377 + 387		(26)	2 × 70.0	15–25 cm		New Tunnel, dry shotcrete, 1 or 2 layers mats + anchors	
96	Switzerland	Nations — Schaub, City of Geneva	Cable & Infrastructure Gallery	1973	982	∅ 3.0		7.1	10		New gallery dry shotcrete, mats + anchors smoothed surface	
97	Switzerland	Rotlaui-Trift	Hydro-power gallery under water pressure	1973	6000			8.0	8–10		New gallery dry shotcrete + mats smoothed surface	
98	Switzerland	Ferdern-Hohtenn	Hydro-power gallery under water pressure	1973	2000	∅ 3.65		10.50	Approx. 5		New gallery dry shotcrete + mats smoothed surface	
99	Switzerland	Lopper Tunnel	Railway	1977	1124		(18)	35	12		Total refurbishment, enlargement of existing profile; dry shotcrete + mats PSL to reduce costs	

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100	Switzerland	Furka Base Tunnel single track + 2 double track sections, *L* = 1'000 m	Railway	1982	15 384	4.5–13	5.9–8.0	25.7–42.4 (single track sections) 56.7 (double track sections)	5–30	36.5 and 44.7 (two different lots)	New Tunnel different profiles, according to rock conditions. mostly U-shape and elliptic profiles, in diff. zones/crossing sections: Circle profile. PSL to reduce costs	
101	Switzerland	S. Antonio-Muralto	Railway	1987	1154			40	25		New Tunnel In zones with anchors: Additional mats	
102	Switzerland	Grengiols	Railway	1987	448	5	5.8 (14.7)	23–26	25		Total refurbishment, enlargement of existing profile; two layers of mats PSL to reduce costs	
103	Switzerland	Gran Sasso I	Laboratory caverns	1987	3 × 130	22	20		30		New caverns Two mat layers + anchors Overburden: 1400 m	
104	Switzerland	Steinachstollen, City St. Gallen	River bypass	1990	2600	∅ 3.50	(11)	9.6	10–25		Infrastructure gallery mats	
105	Switzerland	Spränggi Tunnel	Railway	1990	126		(14.7)	26			Total refurbishment, enlargement of existing profile; two layers of mats PSL to reduce costs	
106	Switzerland	Jostbach	Railway	1990	421		(14.7)	26	25		Total refurbishment, enlargement of existing profile; two layers of mats PSL to reduce costs	
107	Switzerland	Cavaduerli	Railway	1991	336		(16)	29	25		Total refurbishment, enlargement of existing profile; two layers of mats PSL to reduce costs	
108	Switzerland	Grind	Railway	1991	374		(14.7)	26	25		New Tunnel Two layers of mats to reduce costs	
109	Switzerland	Zugwald (Klosters) (part of Vereina railway line)	Railway	Oct. 1995	2154	∅ 7.7 (TBM) or 6.9–8 (road-header)	8.73	46 (TBM)	15–30	first layer: 43.1, inner layers: 56.1		
110	Switzerland	Vereina (Klosters) single track with three double track sections, $L = 3^{*}2000$ m	Railway	Opening tunnel: 11th Nov. 1999	19 049	∅ 7.7 (TBM) 6.5–10.8 Mechanised drill & blast, + Crossing stations	7.05–8.50	46 (TBM) 39 (Drill & blast)	10–45	First layer: 40.6, Inner layers: 57.1	New Tunnel 11.5 km by TBM, 7.5 km mechanised drill & blast. Coated FRP anchors with Epoxy installed Shotcrete to reduce costs. 9 months ahead of schedule Wet shotcrete from crushed rock. Cement: 400–450 kg/m^3. PC Cem II A-M 52.5 (AD 52.5) + 20 kg/m^3 Microsilica	

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						Width (m)	Height (m)	Area (m^2)	Thickness (cm)	Compressive strength (MPa)		
111	Switzerland	Disentiser Tunnel	Railway	Spring 1999	346.1	5.60	6.45 (15.2)	min. 36.9	30–45	probes: 34.4 cube strength: 47.2	2/3 New Tunnel, 1/3 reconstruction + enlarging of existing Tunnel. Difficult geological conditions. Excavator under horizontal jetting-roof. Very close underpass of existing houses. Part of work under full traffic.	
112	Switzerland	Rufenen	Railway	1995	297		(13.2)	23.2			Total refurbishment, enlargement of existing profile; two layers of mats PSL to reduce costs	
113	Switzerland	Mitholz (Loetschberg Base Railway Tunnel)	access gallery, 12% descent	1997	1200	9	7.5		10–25		New Access Gallery Wet shotcrete from crushed rock 0–16 mm + microsilica	Steel
114	Switzerland	Piora (Gotthard Base Railway Tunnel)	Exploring gallery	1997	5552 (TBM) + 750 m drill & blast	∅ 5.2 + galleries 4.5–13	+ galleries: 5–7	21.3	5–20		New Gallery Wet shotcrete from crushed rock + microsilica	
115	Sweden	Norra Länken	Road	1991	630				2.5–10	> 35		
116	Sweden	Lindö/ Tappström	Road	1994	180					> 40		
117	Sweden	Södra Länken	Road	1998.3	16 600	7.8–28	8–12		4–7 + 2	≥ 40		Steel fibre
118	Sweden	Lundby	Road	1998	4100	10.5	7 + 2		4–7	≥ 40		Steel fibre
119	Sweden	Tåsan	Hydro power	1993							Tot:1300 m^3	Steel fibre
120	Sweden	Henriksdal	Water-clearing	1995							Tot:4000 m^3	Steel fibre 1000 m^3
121	Sweden	Södersjukhuset	Hospital installation	1991							Tot:1500 m^3	Steel fibre 300 m^3
122	Sweden	Skarpnäck	Subway	1992	3200						Tot: 4400 m^3	Steel fibre 2100 m^3
123	Sweden	Klippen	Hydro power	1994							Tot: 1000 m^3	Steel fibre 1000 m^3
124	Sweden	Hallandsås	Railway	1996							Tot: 30 000 m^3	Steel fibre 25 000 m^3
125	Sweden	Johannes	Civ. Defence	1995							Tot: 1030 m^3	Steel fibre 600 m^3

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						Width (m)	Height (m)	Area (m^2)	Thickness (cm)	Compressive strength (MPa)		
126	Sweden	Ajaure	Hydro power	1992	230			40	5 + 2			Steel fibre
127	Sweden	Norrala	Railway	1996	3850	7.5	7.20		5–7 + 2.5[1*]	≥ 40	[1*] unreinforced layer	Steel fibre
128	Sweden	Enåsen	Railway	1998	500	7.5	7.20		5–7 + 2.5	≥ 40	150 m mesh reinforced insulated construction	Steel fibre
129	Sweden	Hällåsen	Railway	1998	1800	7.5	7.20		5–7 + 2.5	≥ 40		Steel fibre
130	Sweden	Iggesund	Railway	1992	500	7.5	7.20		5–7 + 2	≥ 40		Steel fibre
131	Sweden	Håbo	Railway	1996	410	12.5	8		6–12	≥ 40		Steel fibre
132	Sweden	Kungsängen-Kallhäll	Railway	1999	1300	12.5	9	100		≥ 40		Steel fibre
133	Sweden	Svealandsbanan	Railway	1997	3420	7.5–12	8.6–9.3		4–10 + 2	≥ 40	4 tunnels	Steel fibre
134	Sweden	Grödingebanan	Railway	1992	8100	7–11.5				≥ 40	14 tunnels	Steel fibre
135	Sweden	Arlandabanan	Railway	1998	8100	7–22		65–200	5–12 + 2	≥ 40		Steel fibre
136	Sweden	Glödberget	Railway	1995	1680	8.0	7.20	67	5–7 + 2	≥ 40		Steel fibre
137	Sweden	Pustberget	Railway	1995	400	8.0	7.20	67	5–7 + 2	≥ 40		Steel fibre
138	Sweden	Hammargårds tunnlarna	Railway	1995	530	12.5	7.5		7.5–12	≥ 40	Mesh reinforced insulated lining construction	
139	Sweden	Luftaskog	Railway	1999	250			115	6–8 + 2	≥ 40		Steel fibre
140	Sweden	Stråvalla	Railway	1999	150			115	6–8 + 2	≥ 40		Steel fibre
141	UK	Falmouth	Sewer outfall	1995							Life duration: 120 years	Steel fibre
142	UK	Brixham	Sewer outfall	1995/96							Life duration: 120 years	Steel fibre
143	UK	Jubilee 102	Metro scheme	1996/97							Life duration: 400 years	Steel fibre
144	UK	Jubilee 104	Metro scheme	1996/97							Life duration: 400 years	Steel fibre
145	UK	Thames tunnel	Twin Tunnels	1996/97							Life duration: 120 years	Steel fibre

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						Width (m)	Height (m)	Area (m^2)	Thickness (cm)	Compressive strength (MPa)		
146	UK	Heathrow Express	Twin track Railway	1996/97							Life duration: 120 years	Steel fibre
147	UK	Daw Mill Colliery	Permanent road way in coal mine	1996/99							Life duration: 20 years Depth: 600 m	Steel fibre
148	US	Mt. Lebanon	Railway	1994								
149	US	Harlan Diversion	Flood Control	1994								Steel fibre
150	US	Cole Park Retention Basin	Flood Control	1995								Steel fibre
151	US	Wheaton Station	Railway	1992/93								